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A new sustainability framework for urban underground space

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In the past two decades, great efforts have been made to develop sustainability solutions for the built environment. One way to measure the efficacy of such solutions is by using sustainability indicators. Greater use of underground space is one of the proposed solutions. However, a detailed review of the current construction sector sustainability indicator systems, such as the Building Research Establishment Environmental Assessment Method and Civil Engineering Environmental Quality Assessment and Awards Scheme, shows that there is a need for a bespoke sustainability indicator framework system tailored to urban underground space. The aim of this paper is to extend previous discussions about the role of underground space in urban areas, with the intention of addressing this shortfall. A new framework is proposed, called Uspear, developed on the basis of the Sustainable Project Appraisal Routine framework revised and restructured specifically for application on urban underground space projects. By the use of an innovative weighting system adopted through extensive stakeholder engagement, the new framework represents a comprehensive indicator framework for addressing sustainability in underground urban space projects.

1. Introduction

Urbanisation is a fundamental driver influencing global development. More than half of the world's population (about four billion people, or 52% of the total global population) currently live in urban areas, and this figure is expected to continue to rise in both developed and developing regions. The UK was the first country that exemplified this trend (Clark, 1996), as in the 2001 census almost 80% of the UK population lived in cities, with this figure rising to 90% over the following 5 years (Denham and White, 2006; UNPD, 2006). Meanwhile, only 9% of its land mass was designated as city (Pointer, 2005; Rogers *et al*., 2012). Projections estimate that by 2050 there will be 6·3 billion (67% of total global populations) living in urban areas (UN, 2012).

As urban populations and cities around the world grow, urban sustainability has become a core focus of attention in the global debate. This change to the city landscape, coupled with concerns over climate change, will affect the basic elements of life for people around the world; these include health, food production, access to clean water and energy (particularly for heating and cooling), waste production (and its removal) and the subsequent impact from and to the environment in which people live. Over the last 100 years in particular, these pressures have led to an increase in demand for land and infrastructure. This is placing ever-increasing demands on the requirements for urban underground space (UUS) (Curiel-Esparza and Canto-Perello, 2012), not least in terms of mass rapid transit (MRT) (Hunt *et al*., 2012) and essential networks for distribution of water, gas, electricity, liquid and solid waste (i.e. sewers, pneumatic refuse disposal) and communications. Moreover, the trend is for this demand for underground space to grow even further and in doing so it could contribute significantly (either positively or negatively) towards the overall sustainability agenda (Bobylev, 2010a; Hunt *et al*., 2008; Laistner, 1997; Rogers and Knight, 2014; Sterling *et al*., 2012).

There remain a number of issues, however, related to wider adoption of UUS and related infrastructures. First, they tend to have limited access points and therefore carry an increased risk of public attacks or sabotage (e.g. multi-utility tunnels that house combined utility infrastructures or underground MRT systems could be a target). Such facilities need to be secured against human intervention or even acts of terrorism. Second, one of the major problems associated with long pedestrian crossing tunnels are criminals' attraction to them (Bobylev, 2009), and certainly over recent decades, this has had implications for the subsequent removal of a number of pedestrian underpasses in Birmingham, UK (Jefferson *et al*., 2006). (Currently in the UK, closed-circuit television cameras are in operation, but there still is a debate regarding the location and effectiveness of these cameras in UUS; see Bobylev, 2009; Izumi *et al*., 2014).

1.1 The relationship between underground space and sustainability

The UN highlighted the following overarching target, which applies to cities, 'to integrate the principles of sustainable development into country policies and programs and reverse the loss of environmental resources' (UN, 2010; UNCED, 1992).

The well-being of future generations depends on managing the earth's resources (Al Waer and Kirk, 2012), so it is necessary to make the use of UUS and associated infrastructure needs sustainable – that is, able to deliver developments that satisfy all three basic elements of sustainability: environmental conservation, social betterment and economic improvement (Ainger and Fenner, 2014; Braithwaite, 2007; Wende *et al*., 2010). Although it has been reported that underground space, and therefore associated underground infrastructure development, can contribute strongly towards meeting the current needs of a sustainable urban environment (Bobylev, 2009; Jefferson *et al*., 2006; Sterling *et al*., 2012; Zargarian *et al*., 2013), questions will arise as to what can and cannot be placed below ground and how wider use of UUS might contribute towards a not only sustainable, but also resilient, future (Rogers, 2009; Rogers *et al*., 2012). For example, could wider use of UUS relieve pressure on surface land use and provide security for key infrastructures? This evidence base is required if specific policies regarding sustainable development of UUS are to be drawn up. Unfortunately, while research is being undertaken to outline these essential role(s) for the subsurface – for example Admiraal (2006) – there is still by no means an overarching plan for UUS in cities (Admiraal, 2015; Admiraal and Cornaro, 2016) or, one might argue, an easy-to-use assessment tool for city planners to assess UUS options (Hunt *et al*., 2016; Makana *et al*., 2016). Therein a strategic vision is required, and this must both identify and consider all UUS services during planning processes with specific reference to new services that might be related to future urban development and sustainability. However, as part of this overarching ethos, natural resources are fast depleting and traditional energy production methods are becoming prohibitively expensive. In addition, clean water is becoming a scarce commodity in several places and climatic conditions are susceptible to considerable change, causing a threat to existing infrastructure and requiring mitigation measures. Underground space could be considered as an area rich in natural resources (Bobylev, 2007; Parriaux *et al*., 2004, 2006) and valuable to all current and likely future developments. Parriaux *et al*. (2008) and Bobylev (2009) identified a number of categories that define the main resources that can be found in UUS and how UUS can be a facilitator in resolving some, but not all, of these issues. These include, but are not limited to, (*a*) infrastructure and facilities (their location below ground in dense urban metropolises could free space above for other uses); (*b*) energy from geothermal sources (thermal energy stored in the underground can be used for heating and cooling purposes); and (*c*) geomaterials excavated from the ground are continually used in manufacturing processes which keep cities running (Bobylev, 2009; Sterling *et al*., 2012), or life functions, which include groundwater for drinking water supplies (Bobylev, 2009). Sustainable underground construction focuses on protection and sustainable use of all of these underground resources, including underground space itself, while at the same time minimising effects on the surface environments from underground construction (Fu, 2012).

When the mentioned principles are followed, UUS use for appropriate urban infrastructure can influence extensively the sustainability of that which is located above ground. This is because locating infrastructures below ground and providing facilities such as better transportation can alter the basis for economic conditions in urban areas – for example by providing the ability to move people/information and resources (including waste) quickly through, around and out of the urban environment. Likewise, the use of UUS can avoid impacts on the social structures therein – for example by avoiding major surface (or even elevated) infrastructure projects, which have been seen to dissect existing neighbourhoods (Porter and Hunt, 2005). In most cases moving infrastructure underground can lead to more urban green space and therefore improved environmental conditions (Bobylev, 2006; Sterling, 1997; Sterling *et al*., 2012). However, wider adoption of UUS is not straightforward owing to its often high initial cost and permanent alteration of the underground environment, which places a distinctive imperative on long-term planning effort. Ultimately, this must take into account all life-cycle costs and benefits and adoption of projects with the most influence on sustainability (Hunt and Rogers, 2005; Sterling *et al*., 2012).

Strong sustainability credentials are now considered to be of primary concern in any new urban development. However, actions to improve sustainability must not only perform well in current circumstances but also continue to accommodate new methods and technologies leading towards a desirable future, however it develops (Hunt *et al*., 2011). Active use of UUS can be observed currently in many cities that are at advanced stages of growth (e.g. Bobylev, 2010b; Evans *et al*., 2009), however, the wider role of increased development in UUS in creating an economically, socially and environmentally sustainable future is being overlooked. Unfortunately issues associated with unabated, ill-planned expansion of UUS in major dense cities are being ignored and will have likely future adverse impacts on the surrounding environment, not least where multiple structures exist below ground (Bobylev, 2013; Hunt, 2005; Hunt and Chapman, 2009; Sterling and Godard, 2000; Williams, 2008; Zhao and Cao, 2011). Undoubtedly, the extensive use of the subsurface will generate interaction with existing structures above and below ground, and these interactions should be planned for (Hunt and Chapman, 2009; Hunt and Rogers, 2005). Therefore, UUS knowledge bases should be improved progressively so that relevant current (and new/improved technologies) that cope well with a range of underground conditions can be employed, thereby reducing risks (Hunt and Chapman, 2009).

Key to all of this is a method for robustly measuring (in the form of indicators, measures and benchmarks) (Boyko *et al*., 2012) underground performance, whether the impacts are felt above or below ground. However, there is no such overarching, comprehensive system or framework able to determine the contribution of increased subsurface use to a more sustainable future. This paper consequently proposes an indicator framework that can be used to identify how UUS should be properly managed and planned for today to achieve a more desirable, less unsustainable future. Arguably, this has not been the case in previous development of UUS (e.g. Goel *et al*., 2012; Hunt and Rogers, 2005). This will make it possible to move steadily from a fragmented decision-making system for UUS to holistic, whole-system(s) thinking. This is essential if wide-ranging sustainability objectives are to be achieved.

1.2 Natural characteristics of UUS

Sterling *et al*. (2012) discussed some possible catastrophic events and examples of how UUS could be beneficial. For example one benefit is the isolation provided by the covering soil or rock from catastrophic events that occur on the surface. This includes resistance to events such as earthquakes, hurricanes, tornadoes, external fires, external blasts, radiation and other terroristic threats. In other words, facilities located entirely in UUS (when built) prohibit trauma or shock that would be experienced by above-ground structures. In addition, use of UUS provides a means by which natural landscape surfaces and vegetation can be preserved, allowing the natural ecological exchanges of the hydrological cycle to flourish. However, in some cases shallow underground utility systems, despite their protected location, can be damaged in a variety of ways by major natural catastrophes, leading to various community disruptions (Benardos *et al*., 2014; Canto-Perello and Curiel-Esparza, 2013; Canto-Perello *et al*., 2009, 2013; Sterling and Nelson, 2013; Yang *et al*., 2014). Additional examples of these natural characteristics of UUS (Bobylev, 2007; Carmody and Sterling, 1993) are provided in Table 1. Some UK examples are provided to highlight the local context and local conditions (being a necessary influencing element of sustainable UUS). From this summary, it can be seen that UUS provides an opportunity for locating facilities and activities underground, which otherwise would be difficult (or even impossible) to install above ground. However, there will always be additional risks – for example fires – which are the most common and damaging problem for UUS, as evidenced with fires in the Channel tunnel (UK to France) in 1996 and 2008 and the Kaprun tunnel (Austria) in 2001.

2. Methodology

This methodology outlines the steps undertaken to provide a comprehensive decision-making tool for assessing, selecting and/or refining the most sustainable underground infrastructure project given a range of alternatives. In summary they are as follows.

- Step 1 – review existing indicator systems (Section 3) to determine whether and how they are appropriate for sustainability assessment of UUS (Sections 3.2–3.6) and, in the case of the most appropriate tool, identify areas requiring modification (Section 3.7).
- Step 2 – implement changes to create a bespoke indicator system (Section 4).
- Step 3 – demonstrate the application of the new framework (Section 5).

3. Step 1: review and assess sustainability indicator systems

3.1 Introduction

An indicator system developed for subsurface use helps to measure how well a system is working and provides a clear understanding of what might be achieved regarding future targets and how far any proposed intervention (i.e. project) is from achieving these goals (Hunt *et al*., 2007). In addition, it is important to consider sustainability as a long-term resolution, without end. Likewise, the contribution that underground systems make to sustainable development should be broken down into smaller units of assessment criteria so that UUS performance can be measured and analysed in detail to facilitate sustainable decision-making processes from project initiation through to its completion and ultimately its long-term use (Jefferson *et al*., 2007). Each of the assessment tools is typically developed using its own unique benchmarking, weightings and calculation system. Naturally, as the tools have been designed to cover different contexts, they emphasise different phases of the development life cycle with different benchmarking and priority levels for the selected criteria, and they rely on different databases, guidelines and questionnaires (Al Waer and Kirk, 2012). The validity of any existing or new indicator is highly dependent on widespread application within projects, as well as its appreciation in a wider context, and the necessary encouragement for its future adoption will involve a great deal of stakeholder participation, which is a core thread of sustainability (Jefferson *et al*., 2007).

Koo *et al*. (2009) stated that numerous sustainability assessment models can be found in the literature. However, the majority of these are applicable to buildings; fewer are related to infrastructure systems and none specifically relates to UUS assessment. In this section, this hypothesis is tested by looking briefly at a range of existing indicators systems.

3.2 International and national indicators

There are several well-established sustainable indicator systems that can be used to assess a whole range of issues related to sustainable development at international levels (e.g. UN indicators) and national levels (e.g. the UK government's headline indicators) and local levels (Hunt *et al*., 2008). Unfortunately these are very generic considerations and do not explicitly mention UUS, although 'land use' itself is specified.

3.3 Leadership in Energy and Environmental Design

Leadership in Energy and Environmental Design (Leed), an environmental building-focused framework system, was developed in 1996 by the US Green Building Council and certifies buildings as silver, gold or platinum (Green Building, 2013). Whereas Leed could be used to assess a building, parts of which may be located below ground, it does not fulfil the remit of a generic UUS assessment tool and fails to be an appropriate choice (Tsai and Chang, 2012).

Characteristics	Description	UK examples
Land use and location	UUS provides an opportunity to locate a facility in a preferred location where a surface option is not possible or acceptable – that is due to the presence of a high density of structures on the surface or limitation of regulations.	The Dinorwig pumped storage power facility (opened in the UK in 1984), the largest in Europe, is mostly hidden underground within a place of natural beauty.
Natural protection	UUS provides protection against mechanical, thermal, acoustic and hydraulic disturbance.	Two of the largest underground bunkers in the UK were built during World War II and can be found in Swynnerton, mid-Staffordshire and Nantwich in south Cheshire.
	Utilities (pipes, cables) and rail networks and roads contained within underground structures are less affected by external environmental impacts and may last longer.	Currently four million holes are dug each year for utility maintenance in the UK with >130 utility companies having access to roads. Utility design lives often underperform.
Resilience to natural disasters and earthquake	UUS benefits from resilience against severe weather conditions – for example hurricanes and tornadoes.	Hurricane winds in excess of 80 mile/h (129 km/h) are known to hit the UK and there are around 30 tornadoes (although mild) occurring each year. The UK is also prone to severe flooding, evidenced most strongly in 2007.
	Resisting damage resulting from severe ground vibration/shaking (e.g. earthquakes), underground structures at depth are less susceptible to damage, and they are less affected by surface seismic waves compared with above-ground structures.	Seismic activity in UK is rare, although there are 200 minor tremors each year. A magnitude 5 earthquake occurs once in every 5 years. The highest recent tremor (5·2) occurred near Market Rasen, Lincolnshire, in 2008 and caused damage to buildings.
	Prevention of water ingress and flooding of the structure itself is required (ITA, 1991). Moreover, the risk of buoyancy needs also to be considered.	Basement flooding is a serious problem in UK cities (e.g. London is particularly susceptible) where groundwater levels have gradually risen as pumping for supply has reduced.
Temperature stability	The uniform thermal environment within soil or rock and the slow response of the large thermal mass of the Earth offer a significant number of energy preservation and energy storage advantages.	Low-grade heat available throughout the UK (at 2 m depth) is ideal for Pasivhaus developments. Deeper geothermal extraction is possible where UK geology is suitable (e.g. Southampton, Cornwall, Yorkshire).
Topographic considerations	In mountainous or rocky areas, tunnels are perceived as a good way of improving transportation alternatives such as railways, roads and so on. Also, they are efficient for river and harbour crossings.	Thames tunnel (opened 1843) was the first passenger (now rail) tunnel to cross under a river. The Standedge trans-Pennine tunnels (1894) were the UK's longest mountainous canal and rail tunnels. Medway tunnel (1996) was the UK's first immersed tube road tunnel.

Table 1. Typical characteristics associated with UUS and UK examples for illustration (Bobylev, 2007; Carmody and Sterling, 1993)

3.4 Building Research Establishment Environmental Assessment Method

The Building Research Establishment Environmental Assessment Method (Breeam) was developed by the Building Research Establishment in 1991, and Breeam has been well received and used within the UK (Hunt *et al*., 2008, 2009). However, it could not be considered as a sustainable UUS development assessment tool, as it once again has an environmental performance focus related to buildings and above-ground surface structures (Campbell-Lendrum and Ferris, 2008; Haapio and Viitaniemi, 2008; Haroglu, 2012; Hunt *et al*., 2007, 2008; Hurley *et al*., 2008).

3.5 Civil engineering assessment tools (Civil Engineering Environmental Quality Assessment and Awards scheme, Horizon and Halstar)

The Civil Engineering Environmental Quality Assessment and Awards Scheme (Ceequal) was developed and is promoted by the Institution of Civil Engineers. Horizon (2012) and Halstar are other frameworks that are applicable to assessment of civil engineering projects, which may be located below ground. However, these assessment-focused tools do not facilitate overall planning (i.e. guidance) and decision-making for UUS (Campbell-Lendrum and Ferris, 2008; Hurley *et al*., 2008; Jefferson *et al*., 2007; Pearce *et al*., 2011; Venables and Milne, 2006).

3.6 Indicators derived specifically for UUS application

(*a*) Fu (2012) developed a range of generic considerations specific to the life cycle of underground space

- site and underground space planning
- structure design
- construction and resource conservation
- operation and maintenance
- retrofit and upgrade.

Unfortunately, this is not accompanied by a specific set of sustainability indicators for UUS. While Hunt and Rogers (2005), Koo *et al*. (2009), and Curiel-Esparza and Canto-Perello (2013) proposed much broader sustainability indicators and decision-support tools for UUS, the focus was towards infrastructure, namely utility installation.

(*b*) Song *et al*. (2013) developed a set of indicator systems for underground space use based on Organisation for Economic Co-operation and Development, Policy Coherence for Sustainable Development (PCSD), EU and Ministry of Environment indicators. The sustainable development model is divided into three main categories of environment, society and economy, with seven, eight and seven indicators under each pillar of sustainability, respectively. With the use of this indicator set, there is a general look into sustainability; however, the shortfall of the system is that no subindicators are included. Therefore, it will provide only an overall perspective on sustainability, which, although useful, does not provide sufficient detail to allow for more informed city decisions with respect to UUS to be made.

(*c*) Li and Parriaux (2012) and Li *et al*. (2013a, 2013b) proposed a new approach to looking at UUS named ‘The Deep City Method’. Within this methodology a set of indicators are presented which consider available UUS resources, including groundwater, geomaterials and geothermal energy. The method is designed to help decision-makers integrate the global potential of UUS into city-scale strategic planning and management of urban underground assets. The method provides operational steps to integrate UUS into the planning process and includes a comprehensive underground asset (supply) assessment. This includes a requirement for in-depth investigation of strategic districts, dynamic forecast of supply and demand potential of underground space and project appraisal of specific UUS users. The focus of the underpinning research is on the development of UUS, which is good; however, the indicators used therein have not been specifically derived to help assess the broader contribution of UUS towards sustainability – hence, it fails to provide the evidence required for the framework developed within this paper.

3.7 Sustainable Project Appraisal Routine

The Sustainable Project Appraisal Routine (Spear) framework, with over 120 subindicators of social, economic, natural resource and environmental performance in 21 headline indicators (Figure 1(a)), was established by Ove Arup and Partners Ltd in 2001 (Braithwaite, 2007). The shading of segments within this dartboard-like structure (Figure 1(b)) shows the performance of groups of indicators – the closer the shading is to the centre of the diagram, the stronger it is in terms of sustainability; conversely, the further away it is from the centre, the weaker it is. Information shown on the diagram is a direct reflection of the quality of information available at the time of data collection, which is used to complete detailed worksheets.

Although Spear does not have a UUS focus (as with some of the other methods outlined herein), it does appear to be the most appropriate broad methodology for refinement to assess UUS projects. This is because the strength of Spear lies in the way it provides a graphical presentation during all stages of a project (i.e. design, construction, operation and maintenance), allowing for (and indicating) continual improvement and evolution over time of the project (McGregor and Roberts, 2003). This enables areas needing improvement to be highlighted, optimisation of sustainability performance (assessed through social, environmental, economic and natural resource indicators), innovation and objective (transparent) reflection on interrelationships, which may ultimately lead to trade-offs (Lombardi *et al*., 2011). While it is neither reward driven nor has it an inbuilt bias, this might be considered a key strength (Holt *et al*., 2010); and although it has been criticised for being oversimplified (Donovan *et al*., 2005), such a simple framework provides sufficient flexibility for it to be wholly appropriate in the design stages of a UUS project, at which point many uncertainties exist and effective communication with internal or external stakeholders is required.

In summary, the main beneficial features of the Spear framework which were detailed by McGregor and Roberts (2003) and which can be utilised in the assessment of UUS are summarised below.

- It gives a graphic presentation of the project during all stages, indicating continual improvement and evolution of a project over time.
- It allows the various aspects of sustainability to be optimised and the interrelationship of these to be assessed.
- It identifies where there may be room for improvement and so achieves optimum benefit.
- The logical and transparent methodology is fully adaptable for various applications.
- It demonstrates the interaction between the various social, environmental, economic and natural resource indicators of sustainability.

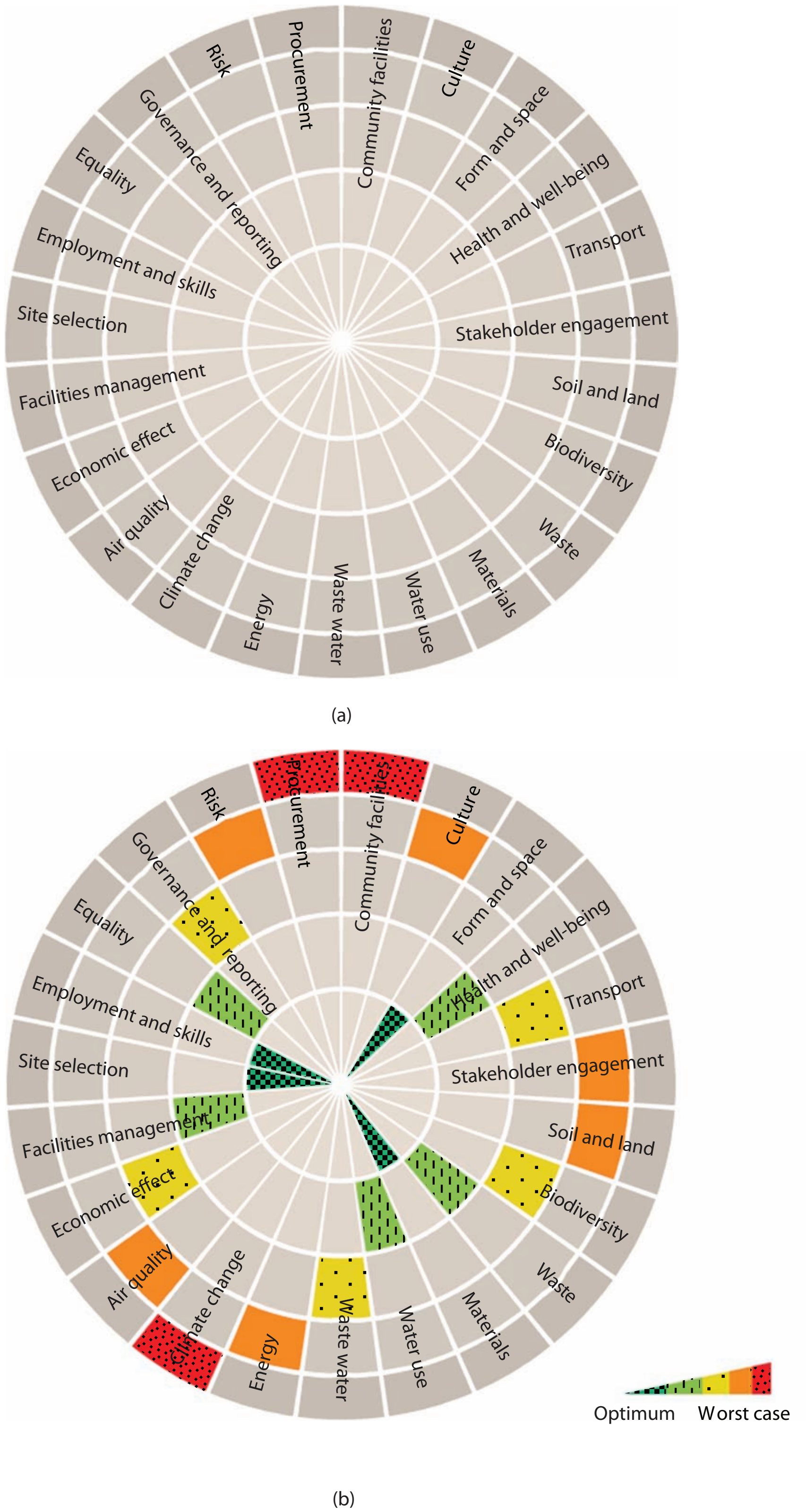

Figure 1. (a) Spear full diagram showing 21 headline indicators (Arup, 2012); (b) Spear full diagram – performance shading included (Arup, 2012)

- The spreadsheet behind the Spear diagram ensures that all assessments are fully audit traceable.
- It prompts innovative thinking to include sustainability in project design and demands team coordination and consensus.

4. Step 2: modelling framework development

In this paper it is proposed that for direct application below ground, the original Spear model would benefit significantly from the following amendments/additions

- proposal 1 – adopting an appropriate weighting system for UUS scores (Section 4.1)
- proposal 2 – exemplification on how UUS can support each specified indicator, where appropriate, through reinterpretation of indicators' narratives for use below ground.

To identify the transformation, the newly developed system is now referred to as Uspear (U indicating underground).

4.1 Implementing a weighting system within the new framework

To assign a simple weighting system to the new framework, the analytic hierarchy process (AHP) decision-based method (Saaty, 1980, 2005) has been adopted. The quantified values contained within the tables were arrived at on the basis of the authors' engineering judgement and experience and are used for illustrative purposes only. (It is appreciated that this judgement, and the inherent value of the weighting of each of the indicators, might be interpreted differently by people from different backgrounds; variation due to different disciplinary perspectives, even though engaged in the common purpose of attempting to deliver objectivity, is the focus of further research.) Derived from the AHP, the relative importance of each criterion in comparison with each other is determined based on a review of previous research and experience gained from similar projects. The steps of AHP development are as follows.

- Stage A – simplify the problem in the form of a hierarchical model. For this study a three-level AHP model was developed in which the

  - *highest level* represents the 'goal' (i.e. sustainable development of UUS)
  - *intermediary level* represents the 'overarching criteria', which in this study are the main pillars of sustainability (i.e. environmental – Table 1; social – Table 2; economic – Table 3), the importance of which for UUS has been assumed equal.
  - *lowest level* represents the 'subsidiary criteria', which in this study are core indicators.

- Stage B: a pair-wise comparison is used to determine the relative importance of each alternative when considering three elements of UUS, namely

  - cost
  - risk
  - opportunity.

  For the case of UUS, by way of example and based on these elements, 'materials' are considered to be more important than 'soil and land' and 'biodiversity', but less important than 'water', 'waste', 'energy' and 'climate change'. These qualitative pairwise comparisons are assigned values according to the scale {9, 8, 7, 6, 5, 4, 3, 2, 1, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9, …} introduced by Saaty (1980). To find the weighting for n criteria, $(n^2 - n)/2$ comparisons have to be made. For the UUS example within the category of the environment pillar with seven core indicators, $(7^2 - 7)/2 = 21$ comparisons have to be made. A matrix evaluating results of the 'subsidiary criteria' with respect to the overall 'goal' is obtained (Curiel-Esparza and Canto-Perello, 2013; Triantaphyllou and Mann, 1995). Such a large number of comparisons within all three pillars require Super Decisions software (Bobylev, 2011).
- Stage C – a consistency ratio is used to assess ranking consistency and is calculated by dividing the consistency index by the random consistency index from Saaty (1980). Generally, a consistency ratio of 0·10 or less is advised (Saaty, 1980). This is achieved in all cases considered here (i.e. Tables 2–4).

In Sections 4.2–4.4 the new framework is modified by taking into account the previously proposed additions and amendments. In brief, the indicator system consists of three sets of indicators and subindicators that are applicable to UUS: environmental (Table 2), social (Table 3) and economic (Table 4). This now includes a weighting system that takes account of costs, risks and opportunities for the project being undertaken. Within the confines of this paper, it is not possible to present a complete set of modified narratives for every indicator; hence, a few carefully selected examples are given within each pillar.

4.2 Environmental pillar

Table 2 demonstrates the environmental pillar of the new framework with relevant weightings applied to UUS indicators. Selected examples to illustrate how indicators are being reinterpreted for UUS are presented.

- *Water monitoring*: controlling groundwater and the processes associated with transferring water from water resources, water usage and disposal of wastewater need to be monitored during and after development of UUS. Water is usually present at some depth below the surface; once it is encountered by man-made UUS activities such as mining, tunnelling or open-cut deep construction, it may directly or indirectly impact groundwater quality and levels. Conversely, groundwater may affect what is placed below ground. As such, measures need to be put in place to ensure environmental impacts are minimised.
- *Daylighting*: lighting is a fundamental consideration in the interior design of a building, and this takes on a fundamental

Core indicators	Weight	Subindicators	Cost	Risk	Opportunity
EN1 – soil and land	0·068	Contaminated land	*	*	
		Soil quality	*	*	
		Drainage systems	*	*	
EN2 – biodiversity	0·036	Protected species and habitats		*	
		Conserving and improving local biodiversity		*	
		Habitat connectivity	*		
EN3 – waste	0·144	Construction waste management plan	*		*
		Waste in operation	*		*
		Hazardous/special waste	*		*
		Composting	*		
		Designing out waste	*		
EN4 – materials	0·070	Materials' efficiency in design/use of recycled or reused materials	*		*
		Environmental and sustainability impacts of materials	*		*
		Healthy materials	*		
EN5 – water	0·140	Water pollution	*	*	
		Water (re)sources	*	*	
		Waste water treatment and disposal	*	*	
		Water monitoring	*		
		Water supply	*		
		Construction	*		
EN6 – energy	0·222	Energy supply	*		
		Energy conservation and efficiency	*		*
		Energy monitoring	*		
		Daylighting	*	*	
		Heat demand	*		*
		Cooling and ventilation	*	*	
EN7 – climate change	0·190	Carbon dioxide management plan	*	*	
		Social impact of climate change	*	*	
		Physical impacts of climate change	*	*	
		Carbon dioxide sequestration	*		
		Economics of climate change	*		
EN8 – noise and vibration	0·130	Construction noise	*	*	
		Vibration	*	*	
Total	1·000				

Table 2. The new framework environmental pillar, weighting and applications; inconsistency = 0·097

and multifaceted importance in the design of underground spaces (Carmody and Sterling, 1993; Goel *et al*., 2012). Underground space usually lacks access to natural daylight, and in underground buildings, steps should be taken to ensure access to natural light to alleviate significantly many of the negative characteristics associated with subsurface facilities. For example the provision of desired quantities of natural light can be achieved in UUS through specular reflectors and correctly sized solar light pipes/wells/tubes (Bouchet and Fontoynont, 1996; Hunt *et al*., 2016). However, for deeper infrastructures, sole reliance on artificial lighting is often required, as is used for purposes such as cinemas, theatres, operating theatres and car parks. This reliance on artificial light (Hanamura, 1990) will have to adopt the most energy-efficient lighting technologies (e.g. light-emitting diode lighting reducing demand by 90% compared with traditional lighting) in order that the impact on energy consumption and carbon dioxide emissions can be curtailed.

4.3 Social pillar

Table 3 demonstrates the social pillar of the new framework. Relevant weightings have been applied to the UUS indicators (prioritising health and well-being, then transport above stakeholder engagement, followed by form and space, then

Core indicators	Weight	Subindicators	Cost	Risk	Opportunity
S1 – community facilities	0·061	Recreation	*		
		Education	*		*
		Healthcare	*	*	*
		Retail	*		*
S2 – culture	0·038	Cultural and religious facilities			*
		Use of environment			*
		Archaeology and local heritage			*
		Art			*
S3 – form and space	0·090	Density; depth and scale	*	*	
		Public, private and communal space	*		*
		Landscape, townscape and visual impact	*		
		Security	*	*	
		Connectivity	*		*
		Microclimatic	*	*	
S4 – stakeholder engagement	0·133	Identification and analysis	*		
		Engagement process and feedback/integrating stakeholders' comments	*	*	
S5 – health and well-being	0·378	Access to green space	*		*
		Community cohesion			*
		Indoor environment	*		
		Social vibrancy	*		*
S6 – transport	0·300	Public transport infrastructure	*	*	*
		Pedestrian design and facilities	*		*
		Cycle design and facilities	*		*
		Waterways/freight traffic	*		
		Low-emission vehicles/private vehicle use	*		*
Total	1·000				

Table 3. The new framework social pillar, weighting and applications; inconsistency = 0·037

community facilities etc.), while selected examples again illustrate how indicators have been reinterpreted for UUS.

- *Landscape, townscape and visual impact*: appropriate steps need to be taken to ensure wider use of UUS to help significantly limit visual intrusion on (and perhaps increase the prevalence of) landscaped areas. Recent examples such the Big Dig project in Boston, Massachusetts, USA, where the central artery system was moved underground, have resulted in many benefits including a corridor of new publicly accessible open space (National Research Council, 2013). Similarly options to place bottomless waste disposal bins (e.g. through pneumatic waste disposal systems or underground location of bin facilities) have the potential to stop the unsightly visual intrusion of overflowing (uncollected) waste from urban centres.
- *Pedestrian design and facilities*: pedestrian access (e.g. underpasses and interconnections between transport modes) has long been placed underground and has the potential to contribute significantly to more sustainable UUS. The recent extensive downtown underground pedestrian connections in Montreal and Toronto, Canada, were initiated as a part of major redevelopment projects (Belanger, 2007; Boivin, 1991), and such adoption, perhaps not on the same scale, can be seen in many major urban centres.
- *Connectivity*: UUS has the potential to provide faster and more pleasant transportation connections between different areas of a city, not least in crowded urban city centres, where there is a lack of available space above ground. The first underground transportation system was opened in London, UK, in 1863, and nowadays MRT, as a form of effective movement of people, is common in developed urban centres.

4.4 Economic pillar

Table 4 demonstrates the economic pillar of the new framework and presents the weightings applied to the UUS indicators (here ranking economic effects > procurement > site selection etc.). The following examples show how the economic indicators have been reinterpreted.

- *Risk management*: for UUS projects the risks are substantially greater than for similar projects above ground. In some cases

Core indicators	Weight	Subindicators	Cost	Risk	Opportunity
EC1 – facilities management	0·097	Usability			*
		Appropriate technologies	*		*
		Whole-life flexibility	*	*	
		Operation and maintenance	*		
EC2 – governance and reporting	0·065	Monitoring and evaluation	*	*	
		Strategy	*	*	
		Risk management	*	*	
EC3 – economic effects	0·284	Value for money	*	*	
		Distortions to local economy	*	*	
		Vitality and regeneration		*	
		Carbon dioxide pricing	*		
EC4 – employment and skills	0·118	Labour standards			*
		Employment creation			*
		Training	*		*
		Access to finance			
		Employment creation in construction/operation	*		*
		Social mobility	*		*
EC5 – site selection	0·163	Site location	*	*	
		Diversity/mixed use	*		
EC6 – procurement	0·197	Local/global sourcing	*	*	
		Procurement strategy	*		
EC7 – equality	0·076	Affordability			*
		Designing for equality			*
		Impacts and benefits	*	*	
		Land tenure			
		Displacement	*		
Total	1·000				

Table 4. The new framework economic pillar, weighting and applications; inconsistency = 0·097

this is because the ground conditions are uncertain or perhaps even in part unknown. This requires an advanced plan for potential future risks to be identified and ways of mitigating the risks to be established.

- *Value for money*: despite the obvious advancement in technology and construction methods, it is estimated that construction costs of UUS facilities are two to four times more than similar ones on the surface (Zhao and Cao, 2011). This issue can give rise to doubts relating to the effectiveness of investing the necessary public funds therein (ITA, 1985). There needs to be consideration of the full range of long-term benefits (i.e. value achieved in economic, environmental and social terms), which indeed is the philosophy at the heart of sustainability.

5. Step 3: example application of the new framework

To demonstrate the effectiveness of the new framework, as well as its practical applications, a case study assessment on a new unnamed library has been undertaken. The results of the assessment are provided herein. A primary focus of this case study was sustainability, which is very much in line with the philosophy of the new framework. The case study is used to show how the framework can be applied and then critiqued to

- identify the weaknesses and strength points in the library
- identify the overall sustainability performance of the library and UUS use.

The first part of the process (modified from the original Spear assessment scoring system) is to rate each indicator from +1 to +5 (worst case to best case, respectively). Figure 2 shows the results after this rating has been applied, with the worst case located at the outermost ring and the best practice shown at the innermost ring of the pie. The advantage of this approach is that it highlights early within the decision-making process which areas are performing/will perform well (in this case EC1, EC3–6, S1–2 and EN4) and those which are performing/will perform badly and need to be addressed (in this case EN2, EN5 and EN8). The outer numbers provided by the new framework show a set of scores once the weightings have been applied. For example in

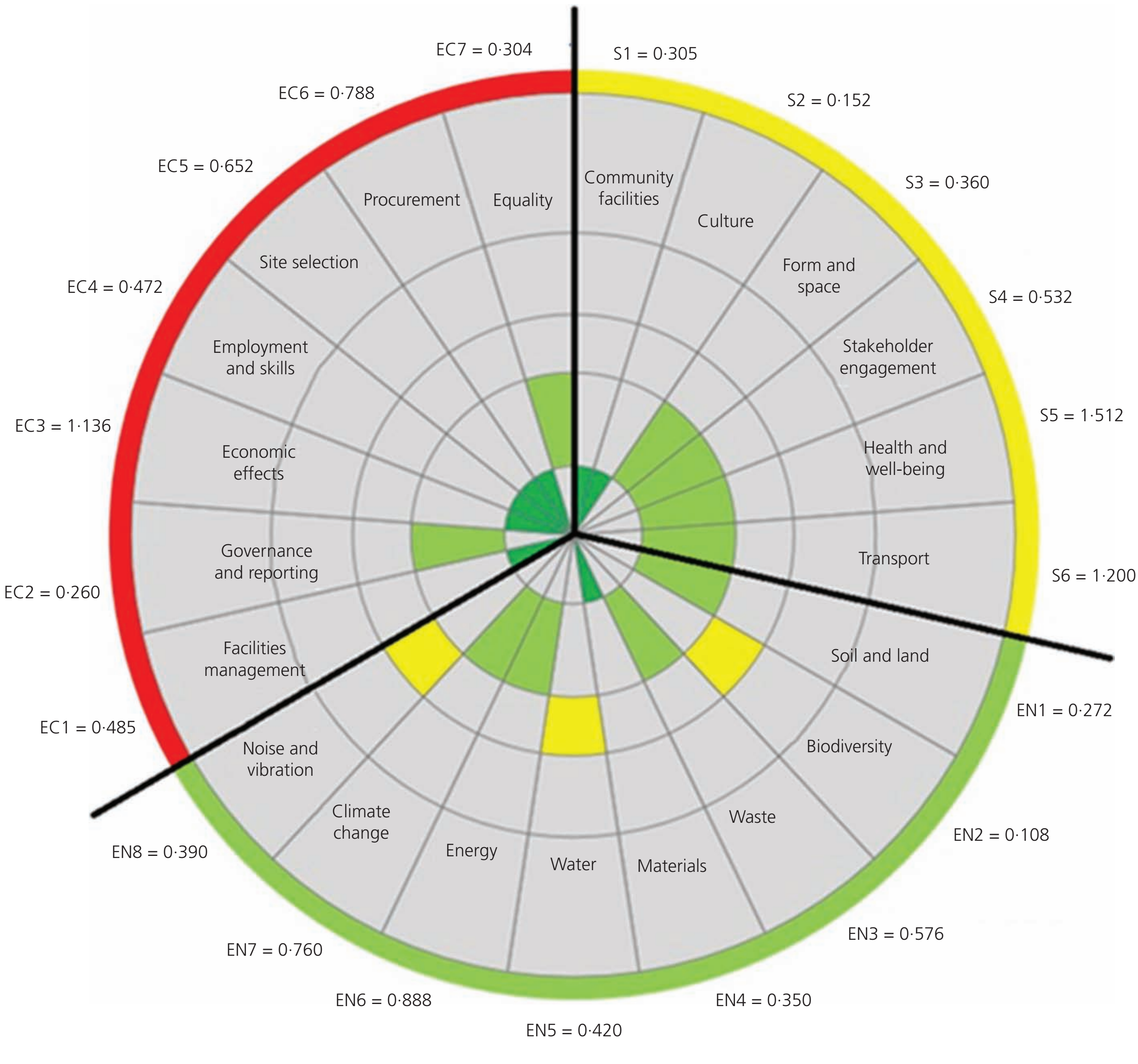

Figure 2. The new framework system showing (un)weighted and weighted scores for the case study example

S1 the initial score was 5, and once multiplied by the weighting factor of 0·061 (Table 3), the factored score is 0·305 (= 5 × 0·061). Likewise, for EN8 the initial score is 3, the weighting is 0·130 (Table 2) and the final score is 0·390 (= 3 × 0·130). The advantage of this weighted set is that it can be used to provide a hierarchy of needs for each pillar of sustainability based on their relative weighted importance. Therefore, out of the worst-performing aspects of this case study, EN5 was deemed most important and at a higher priority than EN8 and then EN2, thus providing a ranking for the order in which they need to be addressed or traded off against each other. The top five ranked aspects of the project (out of 21 headline indicators) were deemed to be health and well-being (S5), followed by transport (S6), economic effects (EC3), energy (EN6) and procurement (EC6). Climate change (EN7) was ranked as sixth. The importance of getting the weightings correct based on as wide a consensus as possible is paramount, reinforcing the argument that all perspectives should be included in the project development process, from the initiation stage (Lombardi *et al*., 2011).

6. Discussion

The new framework has been specifically developed to assess the sustainability of UUS projects. The tool has been developed as a modification to a current sustainability assessment methodology, yet without considering any local or international standards or regulations, and aims to present a simple and user-friendly framework to help decision-makers. This has been done deliberately since what is sustainable is determined locally: local conditions set local priorities, and designing with the particular context in mind is a vital aspect of achieving more sustainable engineering solutions (Hunt *et al*., 2007, 2008). The sustainability assessment for UUS was initiated by setting the goals and objectives of the research followed by a critical review of current indicator systems, as a result of which Spear was selected as an appropriately flexible yet powerful tool. A review of the original indicators led to a modification of the indicators for application to UUS. These have been presented and examples discussed to demonstrate the process that has been adopted for all indicators. Final revisions would then be made to take account of the context, the specific goals of the project in question and the relevant expertise available at the time of the project. The advantages of the new framework can be summarised as follows.

- It provides a means of balancing priorities between and within the three pillars of sustainability.
- It addresses all aspects of sustainability.
- It can be simply adapted and modified on a project-specific basis to account for local contexts and priorities.

However, along with the advantages of the new framework, there are some limitations which need to be considered.

- It is tailored for, and therefore applicable only to, UUS projects.
- It does not incorporate any local or international standards or regulations.
- A series of additional indicators that have been provided originally by Spear are optional and depend on the project. With respect to UUS, some of these additional indicators have been found to be directly relevant. These are mainly from the environmental pillar, related to energy, noise and vibration. This is illustrated in Table 4, along with reasons for retaining the indicator.

The new framework represents a transparent framework for building a comprehensive tool for addressing sustainability issues during UUS development. The breadth of the approach allows UUS development at any stage and any scale, from urban policies incorporating UUS to project level assessments. It takes the well-regarded and much-used Spear platform forward, utilising and enhancing its greatest strengths for application underground. The new framework will benefit from further detailing and tailoring to particular cases where UUS sustainability needs to be addressed. By borrowing from environmental assessments, it is possible to tailor the new framework further according to

- level of initiative – policy, plan or project
- stage of an initiative – strategy, feasibility study, preliminary and advanced design and monitoring
- UUS-specific sector – integrated infrastructures, transport and utilities
- regional context – ground and climate conditions, urban densities, city aspirations and performance in relation to regulations (e.g. local air quality).

The new framework can be modified to meet the specific requirements of any UUS project. Table 5 shows examples of additional indicators specific to UUS projects that were added

Pillar	Core indicator	Subindicator	Comments
Environmental	Energy EN6	Heat demand	Generally, geothermal energy could be considered as a means of contributing towards lower heating or cooling demands. This process is undertaken through different geothermal structures – for example piles, drilling or other foundation systems.
Environmental	Energy EN6	Cooling and ventilation	Underground space use will require ventilation; this should be considered early in the project, taking into consideration natural airflows that can occur below ground (e.g. tube trains), and where there will be requirement for forced ventilation systems to avoid problems with air quality, sustainable solutions should be set.
Environmental	Noise and vibration EN8	Vibration	Vibration noise from construction below ground and ultimately subsurface use are much less likely to affect those at the ground surface. However, vibration and construction (e.g. tunnelling) below ground may cause ground movements, which will need to be assessed (through monitoring) and mitigated.

Table 5. Examples of indicators added to the new framework during this research project

during this framework development to provide a more comprehensive model when considering UUS.

The table shows the level of information that is required should further indicators be deemed necessary on a case-by-case project-by-project basis. On other UUS projects, it might be suggested that indicators within the environmental pillar need expanding to include such aspects as rainwater intrusion, flooding and/or geo-environmental issues such as land subsidence, slip flow, gas and piping. This is wholly reasonable and could be easily integrated in the new framework, although it is worth considering that this would move the framework into fields where other Spear-related frameworks have already been developed at the University of Birmingham to consider such aspects – for example Geospear (Holt *et al.*, 2010). That said, the mere fact that both frameworks are based on Spear facilitates the ability of a user to draw indicators from one to the other, although it should be noted that weightings would need to be added to Geospear as it currently stands.

7. Conclusions

Uspear has been proposed as a decision/assessment support tool with a comprehensive indicator framework that specifically addresses sustainability issues in UUS development. Based on an analytical review of the current trends in urban development and UUS, it was identified that the UUS sector is growing, but facing difficulty due to the lack of availability of appropriate sustainability assessment tools. The review of existing tools and frameworks (e.g. Breeam, Ceequal) has indicated that they cannot be directly applied to UUS development projects and/or their application requires substantial provisional work to match built-in indicator frameworks to UUS specifics. The commonly used standard frameworks naturally have a separate focus, since their development was led by the sustainability needs of above-ground structures and projects.

UUS development most often is not confined to a particular project area, but has an implication for sustainability on the whole urban area, and this has been properly reflected in the wide range of indicators. The new framework has also the right UUS focus, which stems from using the Spear tool and redesigning it based on UUS needs.

The proposed framework can be used to

- explore the hypothesis that wider adoption of UUS will make a significant contribution to a sustainable urban environment, both now and in the future
- indicate the weaknesses and strengths with respect to the increased use of UUS
- aid the decision-making process for stakeholders who are involved in city planning schemes that could integrate better UUS.

In conclusion, the new framework will help policy developers, planners, designers and sustainability professionals dealing with UUS. Since the new framework is UUS tailored, its implementation would require much less time and human resources than the standard non-tailored systems. However, the authors see the new framework as a complementary tool to surface-development assessment systems such as Breeam. Further research is needed to explore the opportunities for using the new framework with systems that provide certification and ranking – the ‘Uspear plug-in’. Nevertheless, in its current form the new framework is an effective and useful tool for understanding UUS development implications within the urban context and an enabler of far more sustainable urban designs; indeed, it can be argued that this is a far more powerful enabler of better design than a system that provides certification and ranking, which should be used only after a fully considered design process to record the outcome. This provides a unique opportunity for identifying and optimising UUS initiatives, leading to better sustainability performance therein.

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